

Demonstration of x-ray lasing in nickel-like tin

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We report the demonstration of x-ray lasing in nickel-like tin at 12 nm by using the prepulse technique in combination with a curved target. A gain length of 4.8 was obtained with a 3-cm-long target of 1 m radius of curvature irradiated by the Asterix iodine laser at 1.315 μm with a total energy of 500 J and a 7.5% prepulse.

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Since the demonstration of high-gain soft-x-ray lasing in neonlike selenium [1,2], one of the main efforts of x-ray laser studies is to develop a small scale system operating at short wavelengths. Recently, a tabletop system was demonstrated with a capillary discharge [3], in which lasing in neonlike argon was observed. Using the tunneling ionization method, a 10-Hz, 41.8-nm laser in palladiumlike xenon was reported [4]. A demonstration of lasing in neonlike scandium, calcium, potassium, and chlorine [5] also showed the possibility of developing a small scale system with a ns-pulse drive system. However, all of these lasing lines are at rather long wavelengths in the xuv range.

One of the efficient ways of producing lasing at shorter wavelengths is provided by nickel-like ions [6–9], with which lasing at 3.6 nm has been demonstrated in gold [10]. Recently, lasing in many nickel-like lanthanide ions has been demonstrated by Daido *et al.* [11], and by Nilsen and Moreno [12]. In one of the experiments [11], lasing at wavelengths from 6 to 8 nm was obtained with a drive energy as low as 200 J. We note that it has been proposed to use low- Z nickel-like ions as a candidate for a tabletop system [13], and preliminary gain observation at 20.4 nm in nickel-like niobium has been reported [14]. It is clear that the demonstration of gain in low- Z nickel-like ions may lead to significant progress in developing a small scale system operating at short wavelengths. This motivated us to investigate x-ray lasing in nickel-like tin.

Nickel-like x-ray lasing in tin is in fact the first proposed nickel-like ion laser [6], and gain production in an imploding gas puff was discussed in 1985 [6]. Experimentally, it has been previously investigated using an exploding foil target [15], in which an indication of amplification on one of the $J=0 \rightarrow 1$, $4d-4p$ transitions at 11.91 nm was reported. We used two techniques in our experiment for gain demonstration. One is the prepulse technique, which has been successful in producing low- Z neonlike lasers [5,16–19]. The other is the use of curved targets, which has been proven to be efficient to enhance the $J=0 \rightarrow 1$ laser in neonlike germanium [20,21] and in nickel-like lanthanide ions [11,12]. With these techniques, we observed x-ray lasing in nickel-like tin with a gain length of 4.8.

The experiment was conducted at Max-Planck-Institut für Quantenoptik on the Asterix IV iodine laser [22]. The laser beam from Asterix was focused by a cylindrical lens array [23] to produce a line focus 150 μm wide and 3 cm long, yielding a $2 \times 10^{13} \text{ W cm}^{-2}$ irradiation on the target surface with a 450-ps [full width at half maximum (FWHM)], 500-J pulse. To produce a defined prepulse, a setup similar to those of previous experiments [18,19,4] was used, in which a pair of 17.5×9 cm mirrors were inserted into the beam path before and after the final steering mirror, which deflects the beam by 6°. The delay between the main pulse and the prepulse was set at 5.23 ns. The highest energy ratio of the prepulse to the main pulse was 15.1%, reducible by inserting calibrated filters between the pair of mirrors.

The principal diagnostics was a time-integrated, spatially resolved transmission grating spectrometer. It was coupled to a thinned, backside-illuminated charge-coupled device (CCD) [24]. Spatial resolution along the target normal was provided by a toroidal mirror with a 50- μm spatial resolution and a magnification of 3. The acceptance angle of the mirror was larger than 20 mrad. A 5000-lines/mm transmission grating with a 50- μm slit dispersed the incident emission perpendicularly to the spatially resolved direction. The grating has a 4- μm period support perpendicular to the grating bars, which disperses the incident emission along the spatial direction. A 1- μm -thick beryllium filter was used to improve the signal-to-noise ratio.

Both planar and curved targets were used. The planar targets are slabs 2.5 cm wide and 1.5 mm thick. Curved targets were prepared by gluing 100- μm tin foils on concave spherical substrates. The radii of curvature used were $R=2.5$ and 1 m, corresponding to compensation angles of 4 and 10 mrad/cm, respectively.

Figure 1 shows a spatially resolved spectrum for a 3-cm-long plasma column with an $R=1$ m tin target. The overall refraction compensation is 30 mrad. A total energy of 517 J and a 7.5% prepulse were used. A bright spot is clearly seen near 12 nm, accompanied by the diffraction by the grating support, which is barely seen. Due to the limited depth of focus of the imaging optics, the target surface is not resolved. The origin of the spatial axis is therefore set at the position of the continuum maximum. The spot near 12 nm seems to be well focused, perhaps due to its smaller emission divergence. One also sees the silicon L edge at 12.4 nm due to the “dead layer” of the CCD [24], and the beryllium K edge at 11.2 nm due to the beryllium filter.

In Fig. 2(a), we give a trace taken along the wavelength coordinate at the spatial maximum of the bright emission

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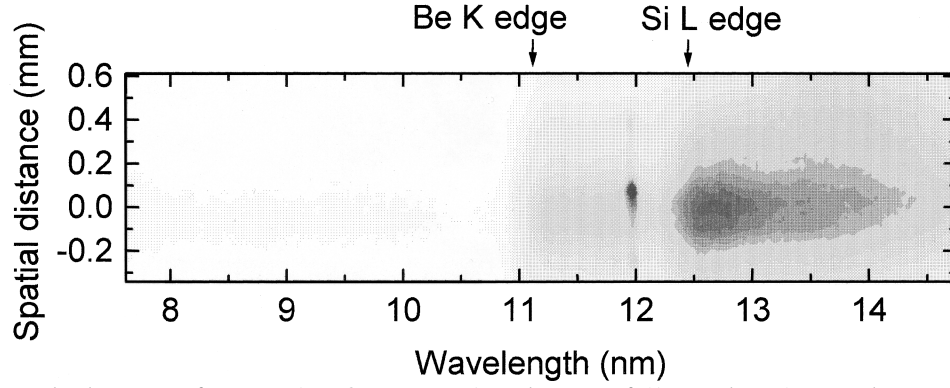


FIG. 1. Spatially resolved spectrum for an $R=1$ m, 3-cm target. A total energy of 517 J and a 7.5% prepulse were used. A bright spot is clearly seen near 12 nm, accompanied by the diffraction by the grating support, which is barely seen. The origin of the spatial axis is set at the continuum maximum. One also sees the silicon L edge and the beryllium K edge.

near 12 nm from Fig. 1. The bright emission is seen to dominate the spectrum. *In situ* calibrated with line emissions from H-, He- and Li-like fluorine, its wavelength was determined to be 11.96 ± 0.05 nm. This coincides with the empirically determined 11.98 nm [25] and measured 11.91 nm [15] wavelength of the $3d_{3/2}4d_{3/2}-3d_{5/2}4p_{3/2}$, $J=0 \rightarrow 1$ transition in nickel-like tin. It is the longer-wavelength partner of the pair of $J=0 \rightarrow 1$ transitions that dominates in elements with Z lower than 70 [7,10–12], and disappears in tungsten and gold [9,10]. The shorter-wavelength partner, predicted to be at 11.5 nm [25], which dominates in ytterbium, tantalum, tungsten, and gold, is not observed, in agreement with the tendency observed in Refs. [11] and [12].

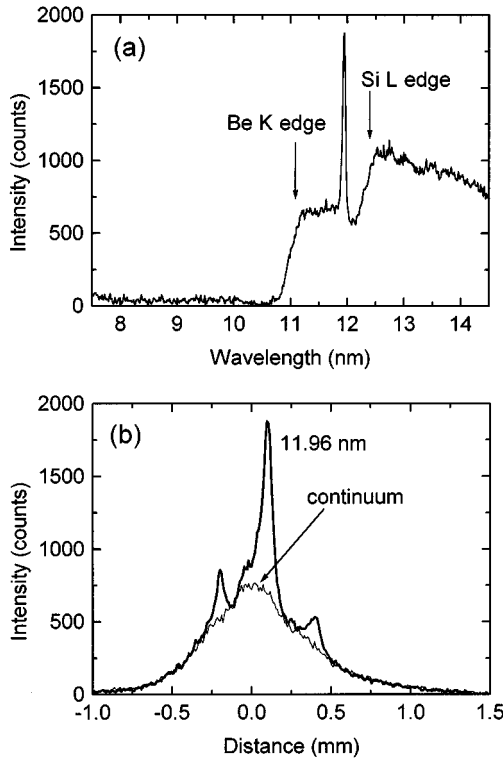


FIG. 2. (a) Trace taken along the wavelength at the maximum of the emission near 12 nm from Fig. 1; (b) a trace along the spatial coordinate at the near 12-nm emission and a background trace close to it from Fig. 1. For the trace of the 12-nm line, the small peaks at both sides are the \pm first-order diffraction pattern due to the grating support.

Figure 2(b) gives the traces taken along the spatial coordinate for the 11.96-nm emission, and a background close to it from Fig. 1. Although the diffraction by the supporting structure influences the spatial profile, we can still see that the 11.96-nm emission has a much narrower spatial profile than the continuum background with a width of about $80 \mu\text{m}$ FWHM.

Both the very localized emission and the high spectral brightness of the 11.96-nm line suggested lasing, which was evidenced by the nonlinear increase of the output intensity with the increasing target length. In Fig. 3, the output intensity of the 11.96-nm line at its spatial maximum is shown as a function of the target length for planar and $R=2.5$ m targets. The data were obtained with a total energy of 500 ± 20 J and a 7.5% prepulse. A fit to the formula of Linford *et al.* [26] gives gains of 0.9 ± 0.5 and $1.3 \pm 0.3 \text{ cm}^{-1}$ for the planar and $R=2.5$ m targets. For the $R=1$ m target we were not able to measure the gain due to the lack of data at different target lengths. However, a small signal gain of $1.6 \pm 0.5 \text{ cm}^{-1}$ could be deduced if a self-emissivity for the lasing emission similar to the planar and $R=2.5$ m targets was assumed. With a 3-cm-long target, this result in a gain length of 4.8.

In our experiment, it was found that the use of the prepulse and the curved target is essential for the demonstration of x-ray lasing in nickel-like tin. With a 2.5-cm-long

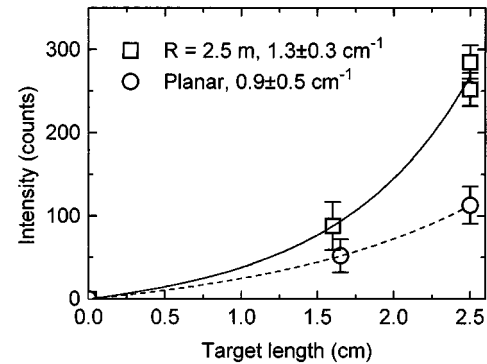


FIG. 3. Output intensity of the 11.96-nm line as a function of the target length for planar and $R=2.5$ m targets. A total drive energy of 500 ± 20 J and a 7.5% prepulse were used. Curves are best fits to the formula of Linford *et al.* [24], which give the gain coefficients shown.

planar target, only when the prepulse was used could we see the 11.96-nm line. The condition given above, i.e., a total energy of 500 ± 20 J with a 7.5% prepulse, optimized the output. Under this condition, the use of an $R=2.5$ m target increases the intensity of the 11.96-nm line by a factor greater than 2 compared to a planar target; the use of the $R=1$ m target increases the intensity by another factor of about 2 if we convert the intensity of the 3-cm-long plasma column to a 2.5-cm target by a gain of 1.6 cm^{-1} .

In connection with our results, it is interesting to review some of the previous experiments. First of all, although the exploding foil target [2] was initially designed for avoiding the refraction loss of the laser beam, it was only after the application of the prepulse technique [16–19] and curved target [20,21] has one seen the long missing $J=0 \rightarrow 1$ line in a neonlike ion dominate. Furthermore, the nickel-like europium laser worked much better with a curved slab irradiated by series of pulses [11] than with a foil target irradiated with a single pulse [7]. A similar phenomenon can also be seen for tin if we compare the result of Ref. [15] with ours. Obviously, for the demonstration of high gain nickel-like las-

ing in low- Z elements, a prepulse or multipulse irradiation scheme in conjunction with a curved target is important.

In conclusion we have demonstrated x-ray lasing in nickel-like tin at a wavelength of 11.96 nm. This finding demonstrates the possibility, as well as an efficient method of extending nickel-like ion lasing to low- Z elements, which may need only low drive power, and therefore contributes significantly to progress towards a small scale system operating in the real soft-x-ray region.

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